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Recent advances in hydrodynamic modeling of the Great Lakes

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Abstract

This paper reviews the progress in hydrodynamic modeling of the Great Lakes made in recent years, specifically numerical modeling of circulation and thermal structure. We examine three closely related components of lake circulation studies: general circulation modeling, high resolution modeling of the coastal zone, and development of hydrodynamic forecasting systems.

Introduction

There has been significant progress in lake hydrodynamic modeling, especially in process-oriented studies, during the last several decades (Schwab, 1992). The earlier focus of physical limnology on short-term processes such as water level fluctuations due to seiches or storm surges was stimulated by the obvious practical importance of these phenomena. Nowadays, with increases in computer power, a whole new set of environmental problems can be addressed using hydrodynamic modeling. In particular, the information on thermal structure and circulation that three-dimensional models can provide is essential for prediction of the transport and fate of biogeochemically important materials in the Great Lakes both for short-term and long-term planning. The progress in long-term general circulation modeling will be addressed in the first part of this paper. Next, we will discuss different approaches to coupling high resolution coastal zone models with the general circulation models. These models were developed because management of the coastal zone requires much more detailed information on currents than coarse resolution general circulation models can provide. Finally, another product of modern technology will be described: a hydrodynamic forecasting system for the Great Lakes. This system represents a significant step in the evolution of large lake modeling from being used primarily as a research tool to applications involving operational, real-time forecasting.

Hydrodynamic modeling for the Lake Michigan Mass Balance Project

A three-dimensional primitive equation numerical ocean model, the Princeton model of Blumberg and Mellor (1987), was applied to Lake Michigan in support of the EPA Lake Michigan Mass Balance Project (LMMBP). The model has a terrain following (sigma) vertical coordinate and the Mellor-Yamada turbulence closure scheme. Model output is being used as an input for sediment transport and water quality models to study the transport and fate of toxic chemicals in Lake Michigan for the two LMMBP study periods: 1982-1983, and 1994 -1995. The first two-year period was chosen for the model calibration because of an extensive set of observational data including water level data from 9 ganges around the lake, surface temperature observations at two permanent buoys, and current and temperature observations during June 1982 - July 1983 at 15 and 50 m depth from 15 subsurface moorings. There is no ice modeling component in the present version of the model, which can be a problem for the annual cycle modeling in general, but not for the chosen period of study: winter of 1983 was one of the warmest winters of the century and therefore practically ice-free. In this paper we will present model results relevant to the 1982-1983 period.

The hydrodynamic model of Lake Michigan has 20 vertical levels, and uniform horizontal grid size of 5 km. The model is driven with surface fluxes of heat and momentum derived from observed meteorological conditions at 8 land stations and 2 buoys from April 1982 to November 1983. To initialize the model, we used surface temperature observations at two buoys located in the southern and northern parts of the lake. Vertical temperature gradients are very small because of convection during that time of the year when the water temperature is less than the temperature of maximum density - 4°C. Therefore, we set vertical temperature gradients to zero, but retained horizontal gradients. The initial velocity field in the lake is set to zero.

The model was able to reproduce all of the basic features of thermal structure of Lake Michigan during the 600 day period of study: spring thermal bar, full stratification, deepening of the thermocline during the fall cooling, and finally a thermal bar in the late fall (Fig.1). Observed temperatures from surface buoys and subsurface moorings were compared to model output. The comparison is quite good

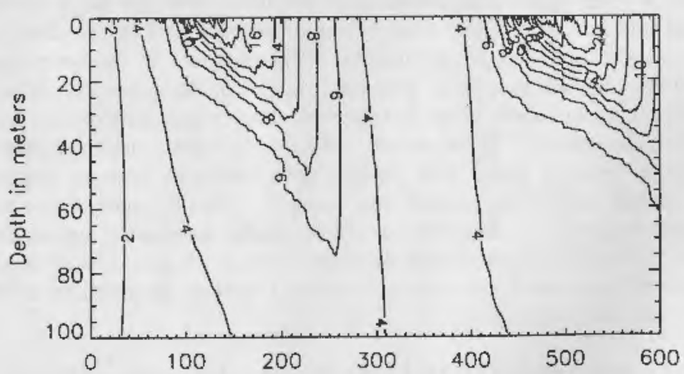

Figure 1. Simulated average temperature profile in Lake Michigan, April 1982-November 1983 (600 days).

for the horizontal distribution and time evolution of the temperature field, but the model tends to generate more vertical diffusion than indicated by observed temperatures. Observed currents were also compared to model output. The largest currents occur in the fall and winter, when temperature gradients are lowest, but winds are strongest. Large-scale circulation patterns tend to be cyclonic (counterclockwise), with cyclonic circulation within each subbasin. Both facts are in agreement with observations.

High resolution coastal zone modeling

In the modeling of large lakes, the numerical grid scales are usually on the order of several hundred meters to a few kilometers. This grid scale is appropriate for large lake barotropic and wind-driven circulation studies, but is often too coarse for specific nearshore coastal zone applications. Localized coastal zone applications demand detailed hydrodynamic information which requires a fine resolution model. The spatial resolution of a fine grid model is on the order of a meter to a few meters. To conduct a fine resolution modeling exercise, there are several unique difficulties and challenges. The least difficult among them is to design a closely spaced grid to match the physical boundaries such as coastal lines and bathymetry. This is often a tedious and time-consuming task. The more difficult challenge is to accurately and precisely set open boundary conditions with the necessary fine spatial and temporal scale. To provide the necessary dynamic boundary conditions precisely at the open boundary requires a careful and deliberate procedure to link a coarse grid model for the large lake hydrodynamic system, which simulates the hydrodynamic boundary conditions on a coarse scale, with a suitable transitional model to meet all the open boundary conditions of the fine resolution model. The linkage procedure of the coarse grid and fine resolution models includes the nesting of two- and three-dimensional finite difference or finite element models.

Shen *et al.* (1995) developed a nested finite-difference model to study the currents and pollutant transport in the nearshore area along the waterfront of the City of Toronto and the mouth of Mimico Creek in Lake Ontario. They used a 2 km grid for Lake Ontario, a 500 m grid for the Toronto waterfront, and a 100 m grid near the mouth of Mimico Creek. The depth grids and time steps were the same for all models. The fine grid model drew the open boundary conditions by interpolating velocities and water levels at the open boundary from those found in the coarse grid model.

The nested finite difference model with a uniform grid system has the advantage of keeping the nnmber of grid points within computer limitations and using the fine grid size appropriate to suit the local applications. Each model step is built on a proven numerical scheme which can be processed efficiently within computer limits. However, the procedure to match coarse grid and fine grid boundary conditions at the open boundary should be carefully investigated. There could be significant error introduced into the submodels if the nested size transition is too drastic or the interpolation scheme is poor. Recognizing these difficulties, Lee *et al.* (1996) modeled the nearshore area of the City of Milwaukee in Lake Michigan using a fine resolution finite element model (Fig.2). The finite element grids at the open boundary were coincident with those on the coarse grid model. The element grid size in the outer layers of the fine resolution grids are gradually reduced. In this application, the grid size reduced from 1 km to 100 m and eventually to less than 10 m at the harbor facility area. The transition from the coarse grid to the fine grid was accomplished without interpolation. It was found that the numerical results were smoother if the elements in the transition layer gradually changed in size.

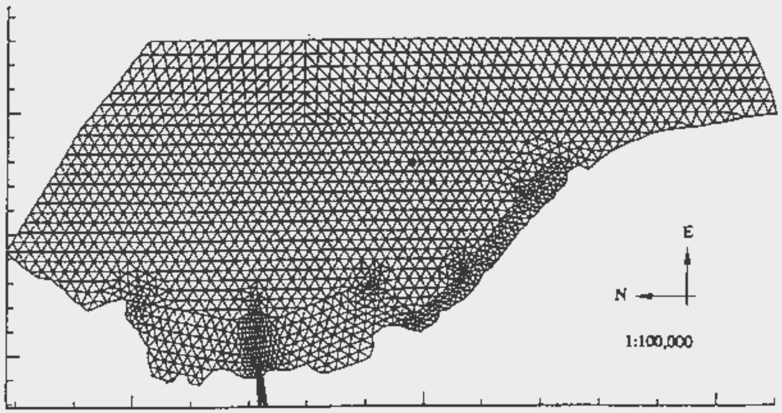

Figure 2. Finite element grid system of the Milwaukee Harbor.

Great Lakes Forecasting System

The Great Lakes Forecasting System (GLFS) is a real-time prediction system that was created for daily forecasting of surface water level fluctuations, horizontal and vertical structure of temperature and currents, and wind waves in the Great Lakes. Three-dimensional lake circulation and thermal structure are calculated using previously described Princeton model (Blumberg & Mellor, 1987), adapted for Great Lakes use at NOAA Great Lakes Environmental Research Laboratory (GLERL) and Ohio State University (OSU). The model is driven by time-dependent surface boundary conditions for wind stress and heat flux. The wave model used in the GLFS is a parametric model developed jointly at the Canada Centre for Inland Waters and GLERL (Schwab *et al.*, 1984). The physical parameters predicted by the wave model are wave height, period, and direction fields. The initial implementation of the GLFS in 1993 and 1994 produced daily nowcasts of system variables for Lake Erie from April to December each year (Schwab & Bedford, 1994). In 1995, the system began to use mesoscale meteorological forecasts to produce 24 hour forecasts of system variables.

In the forecasting mode, the model is run twice per day for a 48 hour period beginning 24 hours previous to the forecast time, thus generating a 24 hour hindcast and a 24 hour forecast. Observed meteorological conditions are used to specify surface boundary conditions for the first 24 hours of the run. The current and

temperature fields from the model at this point in the run are saved to be used as initial conditions for the next day's run. These conditions constitute the 'nowcast' of the present state of the lake. Since 1995, forecasts from NOAA's National Meteorological Center Eta model (Black, 1994) have been incorporated into the system. Forecasts of overlake meteorological conditions are used as boundary conditions for the second 24 hours of the run. The output of this part of the run constitutes the lake forecast. Marine meteorological data are obtained from National Weather Service's (NWS) Cleveland Forecast Office for the nowcast portion of the run. The numerical models are run on the Ohio Supercomputer Center Cray Y-MP8/864 Supercomputer.

Output from the numerical model consists of all relevant two-dimensional and three-dimensional fields at hourly intervals. The main products are a set of two-dimensional color maps of various fields predicted by the GLFS. These maps are generated each morning and represent the current state of the lakes and a 24 hour forecast. The maps include water surface elevation, wind speed and direction, surface water temperature, vertically averaged current, and wave height and direction. In addition, a time series plot of hourly water levels at three stations in the lake is produced to show the history for the last 5 days. A sample output map of temperature cross sections is shown in Fig. 3. This map is a nowcast for 8:00 EDT on August 23, 1995. In the shallow western basin of Lake Erie, the surface mixed layer extends all the way to the lake bottom. In the central and eastern basins, a thermocline is present between 60 and 80 ft. The map products are stored in a computer-readable format for downloading via dial-in or Internet access to the OSU computer system. They are also available through GLERL to users of the NOAA CoastWatch network in the Great Lakes region.

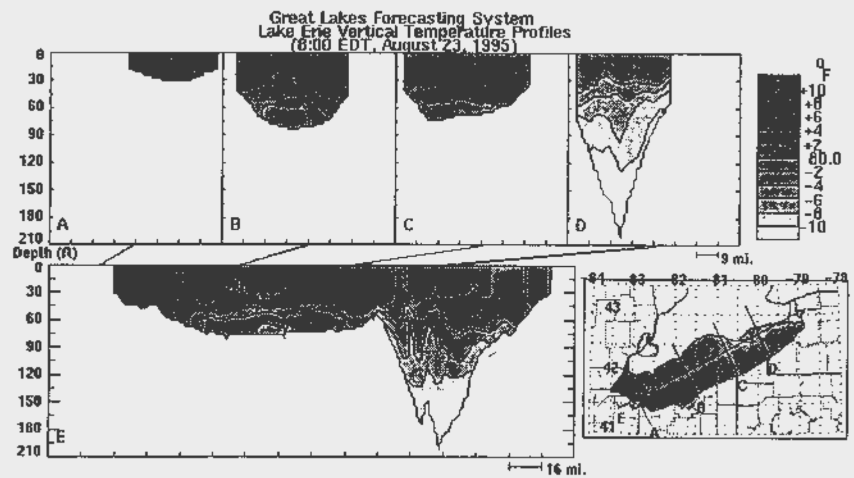

Figure 3. Sample of output map product from the Great Lakes Forecasting System for 8:00 EDT on August 23, 1995

Prospects for the future

Full implementation of the Great Lakes Forecasting System will include: 1) extension to all five lakes, and 2) input from meteorological forecast models to provide 2-day forecasts of lake conditions. It is important that routine forecasts from the GLFS will also make it possible to provide open boundary conditions for high resolution operational nowcasts and forecasts of any limited coastal areas using either nested grid finite-difference or finite-element approach. Further improvement in lake circulation modeling is expected to come from several different sources: refining of model physics and resolution, initial, and boundary conditions. From the point of view of model physics, the most important improvement will probably come from incorporation of ice, which is important for the accurate simulation of the heat budget of a lake, and also because ice modifies the transfer of momentum from atmosphere to water. Further grid refinement in the general circulation models will allow us to describe better circulation in the coastal zone and in areas with steep gradients in bathymetry, and also such processes as coastal upwelling fronts and coastal jets, thermal bar, internal waves, and mesoscale eddies. New observational data, for example, cloud cover from the GOES-8 satellite, and refined meteorological model forecasts will result in further improvement of the accuracy of the forcing functions.

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